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Vol. 29. No. 234. June 1943.

FRACTIONAL DISTILLATION ON BINARY MIXTURES. NUMBER OF THEORETICAL PLATES AND TRANSFER UNITS.*

By A. J. V. Underwood, D.Sc., M.I.Chem.E., A.M.I.Mech.E., F.I.C., F.Inst.F., F.Inst.Pet.

Summary.

For binary mixtures with constant relative volatility, the number of transfer units can be calculated in a form which readily permits of comparison with the number of theoretical plates required for the same separation. The computation can in both cases be greatly facilitated by using a simple graphical method. Any separation with finite reflux can be exactly converted into an equivalent separation with total reflux by using a modified relative volatility and modified compositions.

It is useful to be able to make a ready comparison of the number of theoretical plates and of transfer units required for a given separation by fractional distillation. For binary mixtures, in which the components follow Raoult's Law and the relative volatility may be assumed constant, a number of analytical methods of calculation are available. For the particular case of total reflux, Chilton and Colburn [1] have derived an equation giving the number of transfer units, while Fenske [2] and Underwood [3] have given equations for the number of theoretical plates. For finite reflux, Colburn [4] has given equations for the number of transfer units, and Smoker [5] for the number of theoretical plates. Dodge and Huffman [6] and Hausen [7] have calculated the number of theoretical plates required, assuming a differential change in composition from plate to plate, and consequently their equations actually give the number of transfer units. For the general case of finite reflux, these various equations do not readily permit of comparison between the number of theoretical plates and the number of transfer units, and involve somewhat laborious computations. By making use of the transformation of co-ordinates used by Smoker [5] in deriving his equation for the number of theoretical plates, somewhat similar and readily comparable equations can be derived for the number of transfer units. By means of a simple graphical construction the work of computation in both cases can be greatly simplified. Also, any case of finite reflux can, by a further transformation, be reduced to an equivalent separation with total reflux.

The method used by Smoker [5] for calculating the number of theoretical plates is illustrated in Fig. 1. Referring to axes OX and OY, the equilibrium curve is represented by the equation

$$y = \frac{\alpha x}{1 + (\alpha - 1)x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The operating line is represented by the equation

$$y = mx + b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

* Received 7th April, 1943.

The origin of co-ordinates is now transferred to O', where the operating line and the equilibrium curve intersect. If the co-ordinates of the point of intersection, referred to the original axes OX and OY, are $(k_1, mk_1 + b)$, k_1 is given by the equation

$$mk_1 + b = \frac{\alpha k_1}{1 + (\alpha - 1)k_1} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

or

$$m(\alpha - 1)k_1^2 + [m + b(\alpha - 1) - \alpha]k_1 + b = 0 \quad . \quad . \quad (4)$$

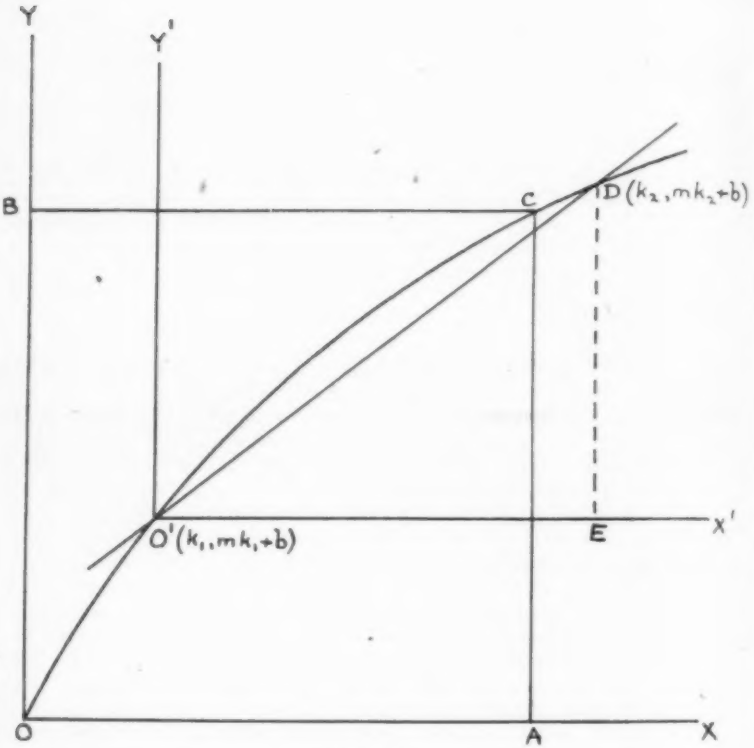

FIG. 1.

Equation (4) has two solutions, representing the two points of intersection of the operating line with the equilibrium curve (continued, if necessary, beyond the normal range of $x = 0$ to $x = 1$). In the following, k_1 is taken as the lower of the two values given by equation (4). For any practical distillation problem, k_1 will lie between 0 and 1 for the operating line of the rectifying section, and will have a negative value for the operating line of the stripping section.

Taking new co-ordinates with the point of intersection O' as origin

$$x' = x - k_1$$
$$y' = y - (mk_1 + b)$$

Substituting in equations (2) and (1), the equation of the operating line becomes

$$y' = mx' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and the equation of the equilibrium curve becomes

$$y' + mk_1 + b = \frac{\alpha(x' + k_1)}{1 + (\alpha - 1)(x' + k_1)} \quad . \quad . \quad . \quad (6)$$

Subtracting equation (3) from equation (6) and putting

$$1 + (\alpha - 1)k_1 = c \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

gives

$$y' = \frac{\alpha x'}{c^2 + c(\alpha - 1)x'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which is the equation of the equilibrium curve referred to the new origin of co-ordinates, O'.

Using the notation of Colburn,[8] the number of transfer units based on change in vapour concentration is given by

$$N_{OG} = \int_{y_n}^{y_0} \frac{dy}{y^* - y} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where y^* is the equilibrium value of y corresponding to x and y is the actual value.

Transferring to the new co-ordinates

$$y^* - y = y'^* - (mk_1 + b) - \{y' - (mk_1 + b)\}$$
$$= y'^* - y'$$

From equations (8) and (6),

$$y'^* - y' = \frac{\alpha x'}{c^2 + c(\alpha - 1)x'} - mx' = \frac{x'(\alpha - mc^2) - mc(\alpha - 1)x'^2}{c^2 + c(\alpha - 1)x'}$$

and

$$dy' = m \, . \, dx'$$

Equation (9) then becomes

$$N_{OG} = \int_{x_n'}^{x_0'} \frac{mc\{c + (\alpha - 1)x'\} \, . \, dx'}{x'\{(\alpha - mc^2) - mc(\alpha - 1)x'\}}$$
$$= \frac{\alpha}{\alpha - mc^2} \int_{x_n'}^{x_0'} \left\{ \frac{mc^2}{\alpha} \cdot \frac{dx'}{x'} + \frac{mc(\alpha - 1) \, . \, dx'}{(\alpha - mc^2) - mc(\alpha - 1)x'} \right\}$$

$$\therefore \quad N_{OG} = \frac{\alpha}{\alpha - mc^2} \left[\frac{mc^2}{\alpha} \, . \log_e \frac{x_0'}{x_n'} + \log_e \left\{ \frac{1 - \dfrac{mc(\alpha - 1)}{\alpha - mc^2} \, . \, x_n'}{1 - \dfrac{mc(\alpha - 1)}{\alpha - mc^2} \, . \, x_0'} \right\} \right] \quad . \quad (10)$$

which gives the number of transfer units required to effect a change in composition from x_n' to x_0'.

The equation derived by Smoker [5] for the number of theoretical plates, N_P, required for the same separation is

$$N_P = \frac{1}{\log_e \frac{\alpha}{mc^2}} \left[\log_e \frac{x_0'}{x_n'} + \log_e \left\{ \frac{1 - \frac{mc(\alpha - 1)}{\alpha - mc^2} \cdot x_n'}{1 - \frac{mc(\alpha - 1)}{\alpha - mc^2} \cdot x_0'} \right\} \right] \quad . \quad . \quad (11)$$

For total reflux, the operating line is $y = x$, and intersects the equilibrium curve at the origin O, so that $m = 1$, $k_1 = 0$, $c = 1$, and $x' = x$. Equation (10) then becomes:

$$N_{OG} = \frac{1}{\alpha - 1} \left[\log_e \frac{x_0}{x_n} + \alpha \cdot \log_e \left\{ \frac{1 - x_n}{1 - x_0} \right\} \right] \quad . \quad . \quad . \quad . \quad . \quad (12)$$

i.e., $$N_{OG} = \frac{1}{\alpha - 1} \cdot \log_e \frac{x_0}{x_n} + \log_e \left\{ \frac{1 - x_n}{1 - x_0} \right\} + \frac{1}{\alpha - 1} \cdot \log_e \left\{ \frac{1 - x_n}{1 - x_0} \right\}$$

or $$N_{OG} = \frac{1}{\alpha - 1} \cdot \log_e \left\{ \frac{x_0(1 - x_n)}{x_n(1 - x_0)} \right\} + \log_e \left\{ \frac{1 - x_n}{1 - x_0} \right\} \quad . \quad . \quad . \quad (13)$$

Equation (12) is the same as the one derived by Dodge and Huffman [6] for total reflux, when calculating the number of theoretical plates on the assumption that there is a differential change in composition from plate to plate. Equation (13), after making the substitution $x = y$, is the same as that given by Chilton and Colburn [1] for the number of transfer units for total reflux.

If now a further transformation of co-ordinates is made by putting

$$x'' = \frac{mc(\alpha - 1)}{\alpha - mc^2} \cdot x' = \frac{mc(\alpha - 1)(x - k_1)}{\alpha - mc^2} \quad . \quad . \quad . \quad (14)$$

then equation (10) becomes:

$$N_{OG} = \frac{\alpha}{\alpha - mc^2} \left[\frac{mc^2}{\alpha} \cdot \log_e \frac{x_0''}{x_n''} + \log_e \left\{ \frac{1 - x_n''}{1 - x_0''} \right\} \right]$$

Now, putting $$\frac{\alpha}{mc^2} = \beta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$N_{OG} = \frac{1}{\beta - 1} \left[\log_e \frac{x_0''}{x_n''} + \beta \cdot \log_e \left\{ \frac{1 - x_n''}{1 - x_0''} \right\} \right] \quad . \quad . \quad (16)$$

Equation (16) is of exactly the same form as the total reflux equation (12) with x'' instead of x and β instead of α. In other words, the calculation for finite reflux by equation (16) is identical with the calculation for total reflux if a modified relative volatility and a modified co-ordinate x'' is used, where β and x'' are defined by equations (15) and (14).

The same relation holds good for the calculation of theoretical plates. For total reflux, equation (11) reduces to :

$$N_P = \frac{1}{\log_e \alpha} . \log_e \left\{ \frac{x_0(1 - x_n)}{x_n(1 - x_0)} \right\} . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

as given by Fenske [2] and Underwood.[3]

If, in equation (11), substitution is made by means of equations (14) and (15), it becomes :

$$N_P = \frac{1}{\log_e \beta} . \log_e \left\{ \frac{x_0''(1 - x_n'')}{x_n''(1 - x_0'')} \right\} \quad . \quad . \quad . \quad . \quad (18)$$

Exactly as before, the calculation for finite reflux is identical with a calculation for total reflux when the modified relative volatility β and the modified co-ordinate x'' is used.

The conversion of a finite reflux calculation to a total reflux calculation can also be derived from equations (5) and (8) for the operating line and equilibrium curve respectively. Substituting

$$x' = \frac{(\alpha - mc^2)}{mc(\alpha - 1)} . x'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and

$$y' = \frac{(\alpha - mc^2)}{c(\alpha - 1)} . y'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

equation (5) then becomes :

$$y'' = x'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

which is the equation of an operating line for total reflux, and equation (8) becomes :

$$y'' = \frac{\frac{\alpha}{mc^2} . x''}{1 + \left(\frac{\alpha}{mc^2} - 1\right)x''} = \frac{\beta x''}{1 + (\beta - 1)x''} \quad . \quad . \quad . \quad (21)$$

which is the equation of an equilibrium curve with relative volatility β.

There is a simple geometrical interpretation of the transformation from the (x, y) system of co-ordinates to the (x'', y'') system of co-ordinates. In Fig. 1 the operating line (for finite reflux) intersects the equilibrium curve at O' $(k_1, mk_1 + b)$ and D $(k_2, mk_2 + b)$, where k_1 and k_2 are the two roots of equation (4). The area $OACB$ represents the usual range of values $x = 0$ to $x = 1$ and $y = 0$ to $y = 1$. If now the co-ordinates x' and y' (referred to origin O') are each transformed by a multiplying factor so that the lengths of $O'E$ and DE become 1, the slope of the line $O'D$ will become 45°. The equilibrium curve, which is a rectangular hyperbola, will be transformed into another rectangular hyperbola. The area $O'DCO'$ between the operating line and the equilibrium curve will then obviously be of the same type as that between an operating line and equilibrium curve for a case of total reflux. The transformations required to convert the co-ordinates (x', y') to (x'', y'') are given by equations (14) and (19),

which can also be demonstrated geometrically. The length $O'E$ is $(k_2 - k_1)$. As k_1 and k_2 are the two roots of equation (4)

$$k_1 + k_2 = \frac{\alpha - b(\alpha - 1) - m}{m(\alpha - 1)}$$

and

$$k_1 k_2 = \frac{b}{m(\alpha - 1)}$$

so that

$$(k_2 - k_1)^2 = \frac{\{\alpha - b(\alpha - 1) - m\}^2}{m^2(\alpha - 1)^2} - \frac{4b}{m(\alpha - 1)} \quad . \quad . \quad (22)$$

From equations (3) and (7)

$$b = \frac{(\alpha - mc)(c - 1)}{c(\alpha - 1)}$$

and, on substituting this value of b, equation (22) gives

$$k_2 - k_1 = \frac{\alpha - mc^2}{mc(\alpha - 1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The length $O'E$, which is $(k_2 - k_1)$ in the (x', y') system of co-ordinates, has to become unity in the (x'', y'') system of co-ordinates, giving the relation

$$x'' = \frac{x'}{k_2 - k_1} \quad \text{or} \quad x' = \frac{(\alpha - mc^2)}{mc(\alpha - 1)} \cdot x''$$

which is equation (14).

Similarly, in order that the length DE, which is $m(k_2 - k_1)$ in the (x', y') system of co-ordinates, should become unity in the (x'', y'') system of co-ordinates

$$y'' = \frac{y'}{m(k_2 - k_1)} \quad \text{or} \quad y' = \frac{(\alpha - mc^2)}{c(\alpha - 1)} \cdot y''$$

which is equation (15).

A simple graphical construction can be used to facilitate the numerical computation of transfer units or theoretical plates from equations (16) and (18). The equilibrium curve and the operating line being drawn, the abscissae of the points of intersection give k_1 and k_2. Then

$$x_n'' = \frac{x_n'}{k_2 - k_1} = \frac{x_n - k_1}{k_2 - k_1} \text{ and similarly for } x_0''.$$

$\beta = \frac{\alpha}{mc^2}$ is then readily calculated from $c = 1 + (\alpha - 1)k_1$.

The further calculation then becomes the same as for a case of total reflux. Having thus determined the factors required for conversion to the total reflux form, the computation of equation (18) can be readily made by using the appropriate nomograms published by Smoker [9] and by Underwood.[3]

Actually it is only necessary to determine k_1 or k_2, as, if one of these is known, the other is readily found from the relation $k_1 k_2 = \frac{b}{m(\alpha - 1)}$. It is

convenient to take k_1 as the lower value and k_2 as the higher value, so that $(k_2 - k_1)$ is always positive. For the operating line for the stripping section k_1 will be negative. The value of c in equations (10) and (11) corresponds to k_1. Exactly similar equations can be obtained in which c is replaced by $c' = 1 + (\alpha - 1)k_2$, the origin of the (x', y') co-ordinates

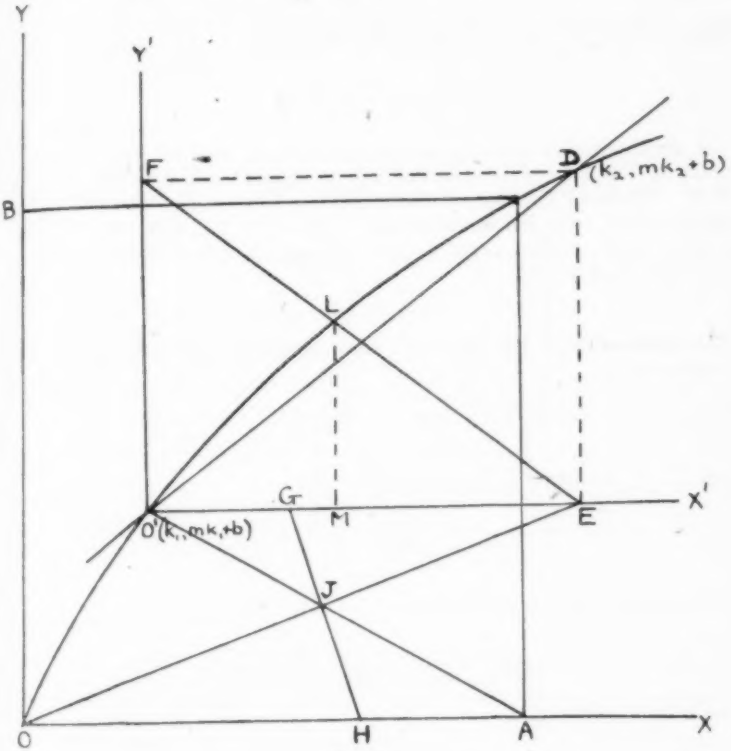

FIG. 2.

then being at the point of intersection D. c and c' are the roots of the equation

$$mc^2 + c\{b(\alpha - 1) - \alpha - m\} + \alpha = 0$$

obtained by substituting for k in equation (4).

Thus $$cc' = \frac{\alpha}{m} \text{ so that } \frac{\alpha}{mc^2} = \frac{mc'^2}{\alpha}$$

and $$\frac{\alpha - mc^2}{mc(\alpha - 1)} = -\frac{\alpha - mc'^2}{mc'(\alpha - 1)}$$

x_n'' can also be obtained purely geometrically as shown in Fig. 2. $O'A$

and OE are drawn to intersect in J. G is any point on $O'E$, and has the abscissa x_n' referred to origin O' or x_n referred to origin O. If a line joining G and J intersects OA at a point H, then $AH = x_n''$.

For
$$\frac{AH}{O'G} = \frac{AJ}{O'J} = \frac{AO}{O'E}$$

Since $O'G = x_n'$, $AO = 1$ and $O'E = k_2 - k_1$,

$$\therefore \quad AH = \frac{x_n'}{k_2 - k_1} = x_n''$$

A simple geometrical construction can also be used to give β. F is a point on $O'Y'$ having the same ordinate as D, and a line is drawn joining it to E. The line FE intersects the equilibrium curve at L. The ratio of the distance of L from DE to its distance from $O'Y'$ (*i.e.*, $EM : MO'$) is then equal to $\sqrt{\beta}$. Putting $O'E$ (*i.e.*, $k_2 - k_1$) equal to l, the line EF referred to axes $O'X'$ and $O'Y'$ is

$$y' = m(l - x')$$

The intersection of this line with the equilibrium curve of equation (8) is given by:

$$m(l - x') = \frac{\alpha x'}{c^2 + c(\alpha - 1)x'}$$

i.e.
$$mc(l - x') = \frac{\alpha x'}{c + (\alpha - 1)x'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Also
$$mcl = mc(k_2 - k_1) = \frac{\alpha - mc^2}{\alpha - 1} \quad . \quad . \quad . \quad . \quad (23)$$

Subtracting equation (24) from equation (23) gives

$$mcx' = \frac{c(\alpha - mc^2) - mc^2(\alpha - 1)x'}{(\alpha - 1)\{c + (\alpha - 1)x'\}}$$

or, using equation (23),

$$mcx' = \frac{mc^2(l - x')}{c + (\alpha - 1)x'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Dividing equation (24) by equation (25),

$$\frac{l - x'}{x'} = \frac{\alpha}{mc^2} \cdot \frac{x'}{l - x'}$$

so that
$$\frac{EM}{MO'} = \frac{l - x'}{x'} = \sqrt{\frac{\alpha}{mc^2}} = \sqrt{\beta}.$$

It may be noted that, if a tangent to the equilibrium curve is drawn at O', the ratio of the slope of this tangent to the slope of the operating line is equal to β. For, differentiating equation (1), the slope of the tangent

at O' is equal to $\frac{\alpha}{\{1+(\alpha-1)k_1\}^2}$ or $\frac{\alpha}{c^2}$. This is not a practically convenient method of determining β, on account of the inaccuracy involved in drawing the tangent. The point is, however, of interest, as Colburn [8] has proposed an approximate method for calculating the number of transfer units, which is based on the assumption that the ratio of the slope of the tangent to the equilibrium curve to the slope of the operating line is constant.

The equation given by Colburn [8] for the number of transfer units based on liquid concentration

$$N_{OL} = \int_{x_n}^{x_0} \frac{dx}{x - x^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

can be integrated by the same method as was used for obtaining N_{OG}. For $x - x^* = (x' + h) - (x'^* + h) = x' - x'^*$ and from equations (5) and (8),

$$x' - x'^* = x' - \frac{c^2 y'}{\alpha - c(\alpha-1)y'} = x' - \frac{mc^2 x'}{\alpha - mc(\alpha-1)x'}$$

Also $dx = dx'$, so that equation (26) becomes:

$$N_{OL} = \int_{x_n'}^{x_0'} \frac{\{\alpha - mc(\alpha-1)x'\}dx'}{x'\{(\alpha - mc^2) - mc(\alpha-1)x'\}}$$

$$= \frac{mc^2}{\alpha - mc^2} \int_{x_n'}^{x_0'} \left\{ \frac{\alpha}{mc^2} \cdot \frac{dx'}{x'} + \frac{mc(\alpha-1) \, . \, dx'}{(\alpha - mc^2) - mc(\alpha-1)x'} \right\}$$

$$\therefore \quad N_{OL} = \frac{mc^2}{\alpha - mc^2} \left[\frac{\alpha}{mc^2} \, . \, \log_e \frac{x_0'}{x_n'} + \log_e \left\{ \frac{1 - \frac{mc(\alpha-1)}{\alpha - mc^2} \, . \, x_n'}{1 - \frac{mc(\alpha-1)}{\alpha - mc^2} \, . \, x_0'} \right\} \right] \quad (27)$$

Using equations (14) and (15)

$$N_{OL} = \frac{1}{\beta - 1} \left[\beta \, . \, \log_e \frac{x_0''}{x_n''} + \log_e \left\{ \frac{1 - x_n''}{1 - x_0''} \right\} \right] \quad . \quad . \quad (28)$$

The corresponding equation for total reflux is derived by substituting α for β and x for x''. Equation (28), together with equations (16) and (18), gives the relation

$$N_{OG} + N_{OL} = N_P \, . \, \frac{\beta + 1}{\beta - 1} \, . \, \log_e \beta \quad . \quad . \quad . \quad . \quad (29)$$

which holds for any separation. For total reflux β is replaced by α.

For two components with low relative volatility, the value of α approaches 1 and the values of c and m are also nearly equal to 1 so that β is also nearly equal to 1. Putting $\beta = 1 + \delta$ where δ is small, then to the first degree of approximation, equations (16), (18) and (29) all reduce to the same form

$$N_{OG} = N_{OL} = N_P = \frac{1}{\delta} \, . \, \log_e \left\{ \frac{x_0''(1 - x_n'')}{x_n''(1 - x_0'')} \right\} \quad . \quad . \quad (30)$$

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RECENT DEVELOPMENTS IN WELDING.*

By C. W. Brett, M.Inst.W.†

So great is the pressure of present activities that there is little or no opportunity to study what certain other industries are doing. Nevertheless, it is most helpful to look beyond the bounds of our direct interests, in order to ascertain if the progress that others are making can be adapted to solve the problems with which we are faced individually.

One of the most remarkable developments brought to the forefront by the stimulus of war is that of successful welding. It is to the credit of a comparative handful of far-sighted men that research work in this direction had been intensified to an extent that enabled war-time needs to be met without delay, although many requirements were so novel and exacting that they had not been attempted on a commercial scale before hostilities commenced.

Engineering progress has provided many such achievements, but few things, if any, have been so widespread in their influence on industry as welding. It is the key to the incredibly rapid production of new merchant ships in America. The same methods are applied with equal success to maintenance and repair, not only to hulls and marine engines, but also to plant of all kinds where components require re-conditioning on account of breakage, wear, or corrosion. At the outset it is most desirable to emphasize that no form of welding calls for greater skill or a more varied background of experience than does repair work, since requirements are seldom identical. Even when the method of procedure is agreed between the operator and metallurgical chemist, and the requisite strength assured, it is skill alone by which perfect alignment is preserved. The usual tolerance allowed is 0·001 plus or minus.

Until quite recently only identical materials could be welded together. Then came certain changes in technique which enabled some degree of variation within the ferrous group. Malleable and cast iron were welded to steel and so on, but the limits were somewhat rigidly defined, and it was thought that greater variations in the respective coefficients of expansion offered an insuperable barrier.

Not long ago a process was perfected which made a clean sweep of most preconceived notions on the subject; it resulted in the achieving of a truly welded union with almost any combination of metals. This important fact is not generally realized, and so far only a few industries, among them the electrical trade in particular, have grasped its importance. Quite apart from repair work, for which the system was primarily evolved, its influence on new production will be potent, to say the least. Aluminium can be welded to steel if needs be, but however striking the dissimilarity between the two metals, tests to destruction, by exerting an increasing pull until something must break, always cause the weaker parent metal to fail first whilst the weld invariably holds fast.

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† Managing Director of Barimar Ltd., Scientific Welding Engineers.

Corrosion is an influence all too well known to those who handle petroleum. It may be that metal spraying, which is an off-shoot of welding, will be used far more widely to combat this trouble in the future. The spraying of zinc in place of the ordinary method of galvanizing is a most useful possibility, particularly in cases of erection work in which the act of riveting has damaged the original zinc coating locally.

The method by which spraying is done is relatively simple. A "gun" is the most complex item of the apparatus. It is rather larger than the hand-piece of a paint spray, and is provided with an automatic feed for wire (or sometimes powder) of the metal it is desired to spray. As the wire or powder is passed through the oxy-acetylene flame it is instantly melted, the molten particles being ejected by a stream of compressed air.

A matt surface can be coated with the same facility as that common to paint. The surprising point about this process is that by the time the particles of metal reach their mark they are relatively cold. This is shown by the ability to coat thin paper without scorching it. Although adhesion is mechanical and not fusive, as in true welding, adherence is extremely good—so good, in fact, that this method is used to build up certain worn components, but scientific welding engineers prefer to apply new material in the more usual form of feed-rods, contending that in this way the grafted and parent metals have a homogeneous unity that is otherwise imposible.

So far as ferrous materials are concerned, gas welding is mainly confined to cast and malleable iron, whilst the electrical method is reserved for steel, although the demarcation is not inflexible. In this connection certain lines of progress are important and should be remembered, because each has opened up new resources, particularly in regard to maintenance and repair. It seems to have escaped general notice that the thickness of the metal that can be handled offers no deterrent to repair. At one time, not so very long ago, a section of metal 2 inches in thickness was almost a borderline case for welding, but nowadays a massive casting having a section of 10 inches in need of repair would not be regarded by the skilled operator as being at all unusual.

To some extent this is linked up with the fading practice of pre-heating before welding is started. The object of this time-wasting practice was to avoid strains being set up owing to sudden local expansion brought about by the heat necessary to accomplish a weld. New methods for controlling the heat-flow have been devised, so that work can be started at once, even to the extent of dealing with the damaged part whilst it is still in position. Obviously accessibility must be reasonably good and subsequent machining unnecessary. To those unfamiliar with this process it may seem impossible to confine the heat strictly to the point of repair, but it is done so effectively that it is possible to touch close up to the seat of fusion without fear of being burned.

It is hardly surprising, in view of the almost infinite variations in modern welding, that a very great deal of it, as applied to repair work, is undertaken by specialists who are willing to work to the closest limits on a guarantee basis.

Most re-conditioning work is needed for one or more of three reasons—corrosion, wear, and breakage. A great deal of work is done in correcting

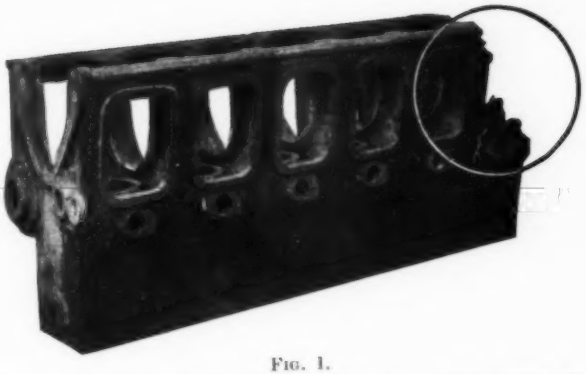

FIG. 1.

COMBINED CYLINDER-BLOCK AND CRANKCASE OF A LARGE DIESEL ENGINE.

Part of the crankcase, at one end, was broken off. The engine belonged to a leading firm of engineers, and they decided immediately to have the damage repaired by welding.

FIG. 2.

CYLINDER-BLOCK AND CRANKCASE SHOWN IN FIG. 1 AFTER IT HAD BEEN RESTORED TO PERFECT CONDITION BY SCIENTIFIC WELDING.

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FIG. 3.

A GEAR WHEEL, SIMILAR TO MANY OTHERS USED IN ALL KINDS OF PLANT. A number of teeth have been broken away.

FIG. 4.

THE MISSING TEETH WERE BUILT UP BY SCIENTIFIC WELDING, RE-MACHINED, AND THE WHEEL WAS AS GOOD AS EVER, SAVING THE OWNERS WEEKS OF DELAY AND THE GREATER PART OF THE COST OF A NEW GEAR.

FIG. 5.

ONE OF THE CYLINDER-HEADS OF A LARGE DIESEL ENGINE.

It was cracked on the water-jacket; two other heads were cracked in a similar way. The ship to which they belonged was held up. A temporary repair had already been made by patching—that explains the presence of the numerous holes in the jacket.

FIG. 6.

THIS IS THE REPAIRED HEAD AFTER ALL THE CRACKS AND HOLES HAD BEEN WELDED.

Unlike a "patch" job, this was a permanent repair, and in a very short time the ship was at sea again. The other heads were repaired in the same way.

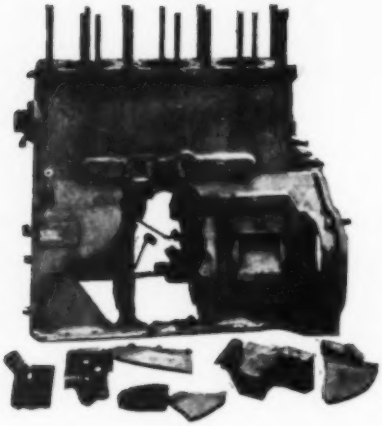

FIG. 7.

THIS ILLUSTRATION SHOWS HOW EXTENSIVE IS THE DAMAGE SUSTAINED BY SOME ENGINE PARTS THAT ARE SENT FOR REPAIR BY SCIENTIFIC WELDING.

It is a three-cylinder block—part of the main engine of a powerful tractor. The whole of the damage to the engine is not shown—the starting engine was also smashed. It will be seen that *both* sides of the crankcase of the main engine are broken out.

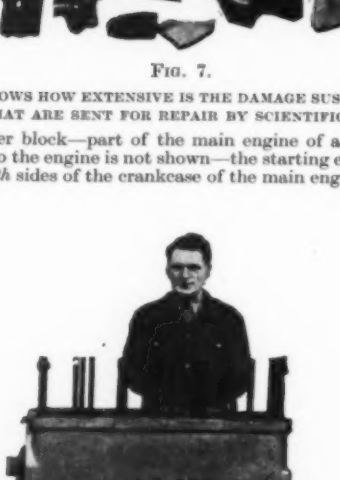

FIG. 8.

HERE IS THE REPAIRED CYLINDER-BLOCK AND CRANKCASE, READY FOR RETURN TO THE OWNERS.

These difficult and extensive repairs were completed within a few days, and apart from the very big saving the owners made on the cost of a new block, they did not lose the use of the tractor during the many weeks they would have had to wait for a replacement.

machining errors and making faulty castings dependable, but such matters are likely to be of lesser interest to readers of this *Journal*.

Few components illustrate the dependability of welding so strikingly as do crankshafts. Fortunately a breakage in this connection is not commonplace, but it does happen from time to time. In these days particularly, prompt replacement is impossible. On the other hand, the reunion of a fractured shaft by scientific welding is no temporary measure, but a permanent and absolutely dependable repair. So much so, in fact, that for years it has been the standard practice of many large transport concerns to have broken shafts welded under guarantee even when replacements were immediately available.

The care taken with work of this kind must be seen to be appreciated fully. Alignment is specially important, but it is the hydrogen "field" process which is largely responsible for the strength secured. Its method of operating is interesting. For a long time the welding of any steel component which had subsequently to receive a high degree of finish was beset with difficulties owing to the almost inevitable pit-marks in the weld metal. These blemishes, whilst not detracting from the strength of the work, could hardly be tolerated on a heavily loaded bearing surface. The reason for them was obvious. Surface marks are due to the affinity of the oxygen in the atmosphere for the molten steel. Far less evident was the cure, although ultimately the complete remedy turned out to be quite simple; for the point of repair was enveloped in hydrogen, and mirror-like surfaces could be obtained at will. At first the supply of hydrogen to cloak the weld was obtained from high-pressure cylinders, but the most favoured method to-day is to use a rod coated with a chemical compound that gives off the required volume of gas directly it is heated in the normal process of repair. This method of welding is so successful that it is freely used to build up worn crank-pins, journals, and other parts. Sometimes oversize diameters are specified, so that after a further long period of duty all that is necessary is precision grinding to restore the shaft to its original limits. This method prevents the need for reducing a worn shaft to below its designed dimensions.

X-ray apparatus of a type specially developed for this work is an important aid towards assuring absolutely reliable results. In the unlikely event of there being a flaw in the weld, this would be revealed and eliminated, however small it might be.

Another point that arises, sometimes in the form of unfounded criticism, is the influence of the weld on heat-treated steel. This is a matter that is always compensated. If the characteristics of the metal are likely to be influenced locally, then restoration is merely a matter of further treatment. A point apt to be overlooked in this connection is the automatic correction that takes place. It is that one layer of electric welding has a valuable normalizing effect on the previous run. This explains why a multi-layer weld has a much finer grain and is far more reliable than heavy single layer weld, which has a coarser crystalline structure. As the final run of welding is not normalized in the manner of the previous runs, an adequate amount of surplus metal is left on the shaft or other component, thus, when finally machined, the weld consists of normalized metal throughout.

So great is the variety of illustrations that can be chosen that it is not easy to select those which will indicate most fully the field of opportunity

open to the many branches of the petroleum industry. In the transport of oil from its source to the delivery of derivatives the valuable applications of welding are legion. By this means pipe-lines are made continuous, and whilst damage and loss from leaking joints are avoided, it is no more difficult to remove a length of piping and insert a new one should this step be desirable at any time.

The construction of tanks and pressure containers of all kinds purely by welding methods is well known, and pumping plant is quickly re-conditioned in the same manner. In many examples of corroded parts a welded component has proved superior to a replacement of the original type. The explanation of this is found in the latitude that is possible to the scientific welding engineer in the choice of weld metal. The manufacturer may have found it necessary to compromise in the choice of material, on account of conflicting characteristics, whereas, when the time comes for re-conditioning, the new metal to be welded in position is chosen with a view to combating corrosive influence or abrasion more actively, or to bring about an increase in strength. In this way the new work helps all concerned by supplementing the producers' efforts to reach a more ideal item of equipment. In view of this objective, of which there are countless examples in service, there is no exaggeration in the claim that a welded item is often far better than a new one. At the same time it is much less costly. Rigid comparisons are, of course, impossible, but it is seldom that re-conditioning by welding does not show an overwhelming saving on the price of renewal. Naturally the figure varies, for the welding engineers may be required to carry out several machining operations after the actual welding has been completed. Often the comparison of cost, as it relates to a new part, can be disregarded in the face of a far greater loss of time and output caused by the breakdown of some important item of plant. If it were not for welding, months of delay might ensue, whereas the resources outlined can be put into operation and completed within a remarkably short time. It is surprising how even elaborate repairs which involve the normal processes of welding followed by machining are commonly completed within twenty-four hours.

It is not often realized that there would be enormous maintenance difficulties in regard to foreign-built vessels now sailing with the Allied Fleet were it not for the benefits of welding. With so many ships cut off from the parent yards and factories, aid in refitting and furnishing replacements must come from other sources. Yet these vessels, many of them tankers, are maintained splendidly.

Steam-engine cylinders are welded from time to time. Sometimes fractures are so inaccessible that portions of sound metal are cut away temporarily so that a perfect weld can be made; then the section removed is replaced without leaving a visible trace of what has been done.

Not long ago an important undertaking handling petroleum urgently required a large compressor. Unfortunately, in course of delivery the cast base, weighing 8 tons, was damaged, a large portion being broken away at one corner. To have replaced the casting, involving elaborate machining operations, would have taken several months. Actually the original casting was made ready for installation within five days by skilful and unremitted welding.

This job was not exceptional in the demands it made upon the welding engineers, but the results were most important, as they united a broken link in a chain of urgent production.

Sometimes an oil-storage tank fails without warning and leakage occurs along a riveted seam. Trouble of this kind arose not long ago when a large container developed this type of fault. The tank, which had been in use only a few years, is used to hold the fuel needed for the central heating system of a large block of flats. Owing to surrounding brick-work it was almost impossible to move such a large container, and as the trouble developed in mid-winter, no time could be lost. It was decided to weld the faulty seam, thus making a permanent seal. There was just room to reach the seat of the trouble, but the restricted quarters, together with fumes from the tank, now temporarily drained, made it impossible for welding operators to work for more than ten minutes consecutively. The welding was therefore carried on in relays, but a life-line was attached to each man, who was under constant observation. The repair was completed in a matter of hours, and the tank refilled. It has not given the slightest trouble since it was welded.

Bearing in mind present-day road transport problems, there is little or no excuse for the immobilizing of vehicles, on account of replacement parts being in short supply. In almost every case components which are thoughtlessly thrown on a scrap-heap impose further strain on supplies of raw material. These items can not only be restored to a condition that is equal to a new part, but the job can be done quickly—often within twenty-four hours. Gear wheels from which teeth are broken and lost can be made whole and dependable again, whilst the problem of an ugly smash is straightened out in a manner that is incredible to all those who have no experience of the resources of modern welding. Cylinder-blocks broken into many fragments, by reason of road accident or frost fracture, are pieced together invisibly and with perfect alignment, whilst worn king-pins and other parts are restored to usefulness and dependability again. This is an aspect of welding which can only be touched briefly upon. It should be emphasized, however, that deeply undercut valve-seats can be built up to their original level again with heat-resisting metal that is also capable of withstanding valve hammer far better than cast iron. The increased efficiency resulting from this work is reflected in reduced fuel consumption, amounting to so much as 20 per cent. in many instances. Building up worn splines and keyways is comparatively simple to the expert.

Most industries must undertake a great deal of experimental work, and this is particularly true of those who handle petroleum and its derivatives. From time to time special plant is required for which there is no general demand, with the result that the cost is high. In regard to this matter welding can help a great deal; since it avoids the use of castings, and, in addition, weight is reduced and, still more important, the need for pattern-making is eliminated. It is not suggested that the foundry is likely to be made unnecessary by welding. This is not the case where repetition work is concerned, but when one or even two or three duplicate pieces of machinery are required welding is less costly.

The same methods can be applied even to gear-cutting. This can be done with such accuracy in flame-cutting machines that gears, pinions, or sprockets formed in this way can be put straight into service and without

the necessity of any additional finishing. One rather elaborate machine recently put into commission incorporates rather more than fifty gear-wheels and sprockets, each one of which has been flame cut from a steel blank.

In the examples quoted there is considerable material for thought and practical application. There is, however, a pitfall. The craftsman always creates an impression of simplicity in his work and the welding repair worker is no exception to this rule. Ambitious work should therefore never be attempted without the essential backing of experience and the advice of the specialist.

Welding goes a very long way towards solving the difficulties and easing the responsibilities of maintenance engineers. At the same time it can offer alternatives of the greatest value in new construction, and provide a solution to complex metallurgical problems which hinder new developments.